Method and Apparatus for Detecting

Multiple Optical Wave Lengths

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BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to detecting
optical signals and, more particularly, to detecting
10 multiple optical wavelengths with optical supergratings.

2. Prior Art

Gratings are optical devices used to achieve wavelength-
dependent characteristics by means of optical
interference effects. These wavelength-dependent optical
15 characteristics can, for instance, serve to reflect light
of a specific wavelength while transmitting or refracting
light at all other wavelengths. Such characteristics are
useful in a wide range of situations, including the
extraction of individual wavelength-channels in
20 Wavelength Division Multiplexed (WDM) optical
communication systems, or providing wavelength-specific
feedback for tunable or multi-wavelength semiconductor
lasers. Gratings are usually implemented by modulating
(varying) the effective index of refraction of a wave-
25 guiding structure. These changes in index of refraction
cause incident light wavelengths to be reflected or
refracted: in the case of an abrupt interface between two

index values, light incident directly on the interface is
reflected according to the well known Fresnel reflection
law.

5   The term "multi-wavelength grating" generally refers to a
grating that is capable of exhibiting optical
characteristics at a number of wavelengths. For example,
a multi-wavelength grating can be a grating that reflects
light at several select wavelengths (which can correspond
10   to specific optical communication channels), yet is
transparent to light at other wavelengths. In some
situations, however, there is a need to set the optical
characteristics for a continuous range of wavelengths,
rather than at specific wavelength values. For example,
15   when trying to compensate for the unevenness of optical
gain profiles in laser cavities and optical amplifiers by
means of an optical grating. However, achieving this
requirement for a continuous range of wavelengths is
difficult to meet with traditional grating technologies.
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Similarly, a range of optical wavelengths may be used
where many communication channels are encoded into a
single optical cable by utilizing different wavelengths
of light; more commonly known as Wavelength Division
25   Multiplexing (WDM) technology. Periodic gratings are
often used to separate or process these channels.
However, periodic grating technologies process one
wavelength, forcing devices intended to process multiple
wavelengths to employ multiple single-wavelength periodic
30   gratings. This is not an attractive solution because, on
top of the additional losses that each grating creates,
even a single grating occupies a considerable amount of
space by today's standards of integration and

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miniaturization. It is thus desired to have a single
device capable of processing several wavelengths in a
space-efficient manner.

5   In the realm of semiconductor lasers, the output
wavelength of semiconductor lasers is largely determined
by the presence of "feedback elements" around, or inside
the laser gain section, which act to reflect light at the
desired wavelength back into the laser. For multi-
10   wavelength operation, multi-wavelength feedback is
needed. Again, single-wavelength grating technology can
only address this demand with a cascade of simple
gratings, leading to the same (if not more notable) loss
and space problems mentioned above.
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One such single-wavelength grating device is a Bragg
Grating. The Bragg Grating consists of a periodic
variation in refractive index and acts as a reflector for
a single wavelength of light related to the periodicity
20   (known as pitch, Λ) of the index pattern; and is
frequently used in both semiconductor systems and fiber-
optic systems. In practice, however, the Bragg Grating
can actually reflect at several wavelengths,
corresponding to overtones of its fundamental pitch.
25   However, these higher-order wavelengths tend to be at
quite different spectral regions than the fundamental
wavelength, thus making the Bragg Grating less than
useful as a multi-wavelength reflector. Moreover, these
higher-order wavelengths cannot be tuned independently of
30   one another.

Other multi-wavelength grating technologies include:
analog superimposed gratings, Sampled Gratings (SG),

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Super-Structure Gratings (SSG) and Binary Supergratings
(BSG).

Analog superimposed gratings are a generalization of the
5   Bragg Grating and are rooted in a principle of
superposition: a grating profile consisting of the sum of
the index profiles of single-wavelength gratings reflects
at all of its constituent wavelengths. Such a grating
relies on an analog index variation, that is, a
10   refractive index that changes continuously along the
grating length (Figure 30). However, it is difficult to
inscribe strong analog gratings using the well known
photorefractive effect, since the change of index under
illumination varies non-linearly, and generally saturates
15   with stronger exposures. Likewise, rendering surface-
relief analog gratings (a typical embodiment for
semiconductors) is made impractical by the difficulty of
reproducibly etching analog features into a surface. The
latter difficulty brought about the introduction of
20   binary gratings, i.e., gratings that rely only on two
refractive index values corresponding to the material
being etched or not etched, illuminated or not
illuminated.

25   Two representations of multi-wavelength binary gratings
are sampled gratings (SG) and superstructure gratings
(SSG). The SG is constructed with alternating sections of
grating and grating-free regions of the waveguide. The
alternating sections produce diffraction spectra having
30   multiple reflectance peaks contained within a (typically)
symmetric envelope. The SG is intrinsically limited in
the flexibility in the location and relative strength of
reflectance peaks, and, because of the large fraction of

grating-free space, is also spatially inefficient. The SG
is therefore particularly unsuitable where a short
grating is required or where waveguide losses are high.

5   With the super-structure grating (SSG), the grating
period is chirped by finely varying the grating pitch,
which corresponds to the length of one tooth-groove
cycle. This can also be thought of as a sequence of
finely tuned phase shifts; common phase profiles include
10   linear and quadratic chirp. Such an implementation in
principle allows arbitrary peak positions and relative
heights, but only at the expense of extremely high
resolution, corresponding to a very small fraction of the
size of the grating teeth themselves.
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Prior art regarding binary superimposed grating synthesis
is presented in Ivan A. Avrutsky, Dave S. Ellis, Alex
Tager, Hanan Anis, and Jimmy M. Xu, "Design of widely
tunable semiconductor lasers and the concept of Binary
20   Superimposed Gratings (BSG's)," IEEE J. Quantum
Electron., vol. 34, pp. 729-740, 1998.

Other methods in the prior art address the synthesis of
"multi-peak" gratings - i.e., gratings characterized by
25   reflectance at several "peaks", which can be controlled
in their position and strength. In these methods, a
grating engineer begins with a set of sinusoids, each
sinusoid corresponding to a single reflectance peak and
weighted according to that peak's desired relative
30   strength. These peaks are added together (i.e.
superimposed; hence the BSG is known as a superimposed
grating) to produce an "analog profile". This profile is
then digitally quantized by a simple threshold method.

For example, if the analog profile value is positive
(above a pre-selected reference) then the corresponding
BSG segment is a high or binary 1 index value; if it is
negative, the corresponding BSG segment is a low or
5   binary zero index value.

However, this approach is inadequate in at least two
areas: firstly, the threshold quantization process
introduces intermodulation, which largely limits the
10   applicability of BSGs synthesized in this manner to
active applications (laser feedback elements and the
like). Secondly, this synthesis procedure is limited to
multi-peak gratings, and offers little or no control over
the individual peak shape. For example, it is entirely
15   incapable of generating flattop channels, as desired by
some communication applications, or of generating the
near-arbitrary reflectance spectra demanded by some gain-
compensation and dispersion-compensation methods.

20   Other methods for BSG synthesis include trial-and-error
methods that are most often computationally difficult and
inefficient.

Therefore, it is desirable to provide a method and
25   apparatus for overcoming the disadvantages noted above in
designing and synthesizing supergratings for detecting
optical wavelengths.

30   BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and other features of the present
invention are explained in the following description,

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taken in connection with the accompanying drawings, wherein:

Figure 1 is a schematic of deep-grating BSG;

Figure 2 is a k-space picture of rationale behind

5   baseband exclusion;

Figure 3 is a prototypical diagram of a lateral BSG in a ridge waveguide;

Figure 4 is a schematic of a prototypical two dimensional (2D) supergrating;

10   Figure 5 is a schematic of a multi-level one-dimensional (1D) supergrating implemented with a 2D BSG;

Figure 6 is a schematic of a prototypical three dimensional (3D) supergrating;

Figures 7a-7d show embodiments of programmable

15   supergratings;

Figure 8 is a schematic of a co-directional asymmetric-waveguide BSG coupler;

Figure 9 is a schematic of a counter-directional asymmetric-waveguide BSG coupler;

20   Figure 10 is a schematic of a counter-directional symmetric-waveguide BSG coupler;

Figure 11 is a schematic of the grid-topology cross bar switch;

Figure 12 is a schematic of an embodiment of a 4-fiber

25   switch, utilizing 6 switching elements;

Figure 13 illustrates a one-photon method of implementing a BSG in optical fiber;

Figure 14 illustrates a multi-photon method (two-photon shown) of implementing a BSG in optical fiber;

30   Figure 15 is a schematic of a demultiplexer employing a 1D BSG;

Figure 16 is a schematic of a demultiplexer employing a 2D BSG;

Figure 17 is a schematic of a static add/drop filter;

Figure 18 is a schematic of a Vernier-tuning dynamic
5   add/drop filter;

Figure 19 is a schematic of a programmable BSG add/drop filter;

Figures 20a-20c are schematics of embodiments of BSG-based wavelength stability monitors;

10   Figure 21 is a schematic of a 2-D BSG network monitor;

Figure 22 is a schematic of a BSG dynamic WDM equalizer;

Figure 23 is a schematic of a gain-flattened optical amplifier;

Figure 24a-24b are schematics of lambda router
15   embodiments;

Figures 25a-25d are schematics of embodiments of BSG dispersion-slope compensators;

Figures 26a-26b are schematics of tunable dispersion compensators;

20   Figures 27a-27c are schematics of a variable-feedback supergrating laser;

Figure 28 is a schematic of beam combiners, in coupled-waveguide and 2D BSG embodiments;

Figure 29a is a schematic of a BSG-based isolator;

25   Figures 29b-29c are schematics of 4-port coupled-waveguide circulators;

Figure 30 is an analog index profile from a plot of refractive index change delta-n (Δn) versus distance (x);

Figure 31 shows a BSG index profile of Δn versus distance
30   x and the corresponding surface-relief implementation;

Figure 32 is a block diagram showing a standard topology for Delta-Sigma modulation;

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Figure 33 illustrates a synthesis technique for a BSG
using induced-symmetry;

Figure 34 illustrates a synthesis technique for a BSG
using super-Nyquist synthesis; and

5   Figure 35 is a flow chart showing method steps of one
embodiment of the present invention for synthesizing a
BSG.

Figures 36a and 36b illustrate a simplified example of a
demultiplexer comared with discrete components.

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Figures 37 - 45 illustrate embodiments that employ a
pattern of pixels that provides a photonic band gap
structure

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Although the present invention will be described with
reference to the embodiments shown in the drawings, it
should be understood that the present invention can be
20   embodied in many alternate forms of embodiments, and it
is not intended that this invention is limited only to
the embodiments shown.

For the purposes of this invention, gratings are
considered to be optical devices used to achieve
25   wavelength-dependent characteristics by means of optical
interference effects.

Starting with Binary Supergratings (BSG), it will be
appreciated that there are two main properties that
30   differentiate the BSG from other grating technologies.
The first is that the BSG relies on a discrete number of

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refractive index levels. This number is historically 2
and hence the BSG is known as a binary grating. For the
sake of clarity and illustration this description will
focus on the binary embodiment of the present invention,

5   however, it will be appreciated that in alternate
embodiments any suitable number of discrete levels of
refractive index may be used. For convenience in the
claims, the term supergrating will be used to refer to
gratings with two or more values of index of refraction,

10   unless specifically stated. The second defining property
of the BSG is that the grating resembles a sampled
structure characterized by a sample length. This refers
to the fact that transitions between the grating's index
levels cannot occur at arbitrary positions but, rather,

15   occur at multiples of the sample length. The BSG is thus
similar in definition to a digital signal pattern – i.e.,
a discrete sampled waveform. Thus, the BSG can be
described by a series of (often binary) digits,
indicating the refractive index setting at each sample

20   point (see Figure 31).

Referring now to Figure 35, BSG design involves several
key choices. Step 351 selects the refractive index levels
for the device, as determined from material parameters

25   and lithographic or photoinscription constraints. Step
352 then determines the desired sample length,
considering the desired wavelength range for the grating
and the available lithographic resolution. Step 353 sets
a total device length for the grating, limited by the

30   available physical space and the technological
limitations of the inscribing process. It will be
appreciated that the methods described herein are for
determining grating patterns for surface-relief gratings;

however, in alternate embodiments the methods may be
readily adapted to fiber grating patterns, or to
programmable implementations. The next step 354 converts
the desired grating's diffraction characteristics to the
5   Fourier domain using a Fourier approximation. These
diffraction characteristics can be reflective,
transmissive, co- or counter-directional coupling, or
scattering in character, or any combination thereof; it
will be appreciated that "reflectance" and "reflection"
10   can be replaced by "cross-transmittance" and "cross-
transmission" throughout this document. Guided by the
Fourier approximation, the designer can initially design
the grating by its Fourier spectrum. As will be shown
below, this step can also implement feedback to account
15   for various inaccuracies of the approximation in order to
improve the final result. Alternatively, any method for
the design of an analog refractive index profile to
achieve the desired diffractive characteristics is
suitable, and many are known in the art.
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The next step 355 performs a quantization of the analog
index profile. Delta-Sigma modulation is one such
quantization technique that can be used and can be
efficiently implemented. It will be appreciated that in
25   alternate embodiments any suitable quantization technique
that conserves Fourier information within a spectral band
may be used. Methods of synthesis and resultant gratings
that use a threshold quantization technique such as that
shown in the cited reference by Avrutsky, et al., which
30   does not conserve Fourier information within a spectral
band are disfavored, but may be useful in some
circumstances. In the case of two dimensional or three
dimensional radiation processing, where radiation

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traveling in two or three dimensions is significant, and
a pixel array extending in two or three dimensions is
significant, any quantization method may be used to
design an apparatus that falls within the definition.

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The next step 356 determines the BSG's actual diffractive
characteristics using an exact technique such as one
known as the transfer matrix method. This calculation
determines residual errors of the Fourier approximation,

10   or other synthesis method used, and quantifies an error
that can be taken back into the Fourier domain and added
to the result of the step 353 if step 357 determines that
the error exceeds a predetermined threshold. This process
can be repeated as necessary, although one repetition is

15   often sufficient. It will be appreciated that any
suitable technique for determining error between the
desired diffractive characteristics and actual
diffractive characteristics may be used.

20   Referring now to each of the above steps in more detail;
in step 353, the Fourier approximation is a mathematical
relation that relates a grating's diffraction
characteristics (which can be reflective, transmissive,
or scattering in character, or any combination thereof),

25   to the structure of its index profile. In other words,
single-wavelength gratings have reflectance spectra
characterized precisely by their periodic structure, and
simple superimposed gratings have reflectance spectra
characterized by their wavelength or reflectance spectra

30   components. Therefore, the diffraction spectrum of a
grating can be related to the Fourier transform of its
structure — the Fourier transform being the standard

method for evaluating the "frequency content" or "wavelength content" of a waveform.

Thus, it will be appreciated that the invention
5   advantageously uses a Fourier approximation to provide a means (the inverse Fourier transform) for generating an analog refractive index profile from the desired reflectance specifications.

It will also be appreciated that the step of quantizing
10   the analog index profile (step 355) can be performed regardless of how the analog profile was determined. In other words, the analog profile need not have been obtained using Fourier-based methods.

15   The following examples illustrate Fourier Approximation for BSG synthesis:

Synthesis Of Simple Peaks

20   In some situations, such as with laser feedback elements, the BSG is desired to reflect light at a given set of wavelengths, and to do so with the highest wavelength selectivity possible. That is, the specification is for simple peaks with minimal channel width. Such peaks can
25   be derived from the superposition of sinusoidal profiles:

$$\sum_i a_i \cos\left(\omega_i x + \phi_i\right)$$

where a_i, ω_i, and ϕ_i are the amplitude, spatial frequency and phase of the ith peak respectively, and x is the
30   position along the grating's length. Most situations dictate the amplitude coefficients. However, many do not require anything specific of the phase.

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In general, component phases should be selected such that
they minimize the maximum height of the superposition
(which consequently flattens the overall envelope), given
5   the component amplitudes. The use of phase information to
produce a flat envelope can greatly increase the
efficiency of the grating. This illustrates a general
principle of BSG design: in most cases, the analog index
profile (before quantization) should preferably have an
10   envelope that is as flat as possible. This is desirable
because a flat envelope represents an even distribution
of grating strength, and makes more efficient use of the
available index modulation.

15   The phase optimization step in accordance with this
invention facilitates large increases in a BSG's
reflective efficiency. It will be appreciated that
increasing the number of reflective peaks produces a sub-
linear increase in the required index modulation. That
20   is, in order to double the number of peaks, but maintain
the same peak reflectance, the index step does not need
to be doubled.

Synthesis Of Bandpass Channels
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A grating is often required to separate or select
wavelength division multiplexed optical communication
channels. These channels are described by their
wavelength (position) and their bandwidth (width).
30   Gratings are also typically accompanied by specifications
of the strength of the reflection and the spectral
flatness of the channel. Such bandpass filter design is
commonly encountered in FIR filter theory, and thus many

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approaches to its solution exist. The technique presented
here is based on the method of windowing:

The main principle in the synthesis of structured grating
5   spectra, such as the bandpass filter, is the use of
analytically determined solutions to an approximated
design problem: certain filter shapes, such as the flat-
top filter, are known to correspond to certain
mathematical functions. For example, it is known that the
10   sinc function with the form:

$$\frac{\delta\omega}{\pi}\text{sinc}(\delta\omega\ i) = \frac{\sin(\delta\omega\ i)}{\pi i}$$

where i is the BSG segment number, corresponds to an
ideal lowpass filter of width $\delta\omega$. This filter can be
15   converted into a bandpass filter centered about the
frequency ω_c by multiplying it with an appropriate
sinusoid, resulting in the filter:

$$\frac{\Delta\omega}{\pi}\cos(\omega_c i)\,\text{sinc}\left(\frac{\Delta\omega}{2}i\right)$$

where the peak is centered about ω_c and has a width of
20   $\Delta\omega$.

Unfortunately, this filter, characterized by an abrupt
transition from the passband to the stopband, requires an
infinite length for its implementation. Simply cropping
25   the filter to the desired length produces undesirable
oscillatory features known as Gibbs phenomena. This is a
common issue in FIR design, and one approach to its
solution is the method of windowing.

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The method of windowing views cropping as a
multiplication by a window function that is zero in the
cropped regions. Theory views the cropping operation as
multiplication by a "rectangular window" which equals 1
5   within the region to be kept, and 0 outside in the
sections to be cropped. The theory argues that this
rectangular window is responsible for the Gibbs
phenomena.

10 Window functions that can be used for cropping generally
make the bandpass filter non-ideal by producing a finite
"transition width" between the passband and the stopband,
in contrast to the ideal filter, which requires no width
for the transition. However, FIR filter theory suggests
15 several acceptable, albeit non-ideal, window functions.

One such window function is the Kaiser window – a window
function conceived with the ideal lowpass (and thus
bandpass) filter in mind, and which allows the designer
20 to customize the transition characteristics through a
parameter β. The Kaiser window is thus suitable for BSG
synthesis and provides the added flexibility of
controlling the shape and sharpness of the reflectance
channels. However, this is only one of many FIR
25 techniques that can be used to achieve this result, and
BSG synthesis by Fourier methods is not restricted to
this particular method.

It will be appreciated that the analog profile
30 corresponding to a flattop channel makes most use of the
center of the grating. As with the multi-peak case, this
situation is undesirable as it makes inefficient use of
grating resources away from the center. A convenient

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solution to this problem is to stagger the waveforms associated with individual channels when superimposing them. Together with a phase-optimization technique such as that used for the multi-peak grating, this procedure

5   can enable very efficient use of the grating's resources.

In some embodiments the reflectance specifications do not correspond to particular elementary shapes such as band pass channels or peaks. Gain compensation profiles for

10   optical amplifiers and dispersion-compensation gratings fall into this category. In these embodiments, gratings may be synthesized using the discrete Fourier transform (DFT).

15   The discrete Fourier transforms and the related fast Fourier transform (FFT) are versions of the Fourier transform that operate on a finite number of sampled points. Being related to the regular Fourier transform, the Fourier approximation and its implications on BSG

20   synthesis carry over to the DFT. A DFT operating on a set of 1 real-valued points returns a set of 1/2 independent frequency components. Thus, a desired grating with 1 segments may be assigned reflectance values at 1/2 wavelengths, but not between wavelengths.

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An example of BSG synthesis using the DFT is carried out as follows:

The frequency-domain specifications are inserted into an

30   array of length 1, the intended device length (in terms of number of samples), in a manner suitable for the inverse-DFT operation. This can be done by "sampling" the continuous version of the Fourier-domain specifications

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at certain points, or, alternatively, by "drawing" the
specification directly in the form suitable for the DFT.
The inverse-DFT of the array is then determined. Various
known forms of "smoothing" can be applied to the
5   resulting waveform in order to reduce oscillatory
features between the frequency samples.

Once the analog index profile has been synthesized, it
may require several modifications. One such modification
10   is filtering by a discrete-sum filter. Another
modification is that the waveform should be scaled to a
level appropriate to the upcoming Delta-Sigma modulation
stage. For example, this can be accomplished by rescaling
the waveform to have an amplitude of 1.
15

Quantizing Or Delta-Sigma Modulation (DSM)

The Fourier domain synthesis presented up to now produces
an analog grating profile. However, the BSG requires a
20   discrete profile utilizing only a small number (usually
two) of index values. It will be appreciated that in
alternate embodiments any suitable number of discrete
values can be used, such as for example, an Octal Super
Grating (OSG). One technique for the quantization (i.e.,
25   discrete rendering) of the grating profile is Delta-Sigma
modulation. However, any suitable quantization techniques
can be used.

A preferable requirement for the quantization of the
30   analog profile by Fourier methods is that it conserves
spectral information in the frequency band of importance.
Delta-Sigma modulation, for example, is designed to
"filter out" quantization noise from a given frequency

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band, leaving the spectral information in that band
mostly undisturbed. Other quantization methods can also
be applied, with improvements, such as an accounting for
grating effects that are not evident in the frequency

5   domain. In any case, the selected quantization method
preferably conserves small-amplitude spectral features in
the band of importance, as required by the Fourier
approximation, which becomes exact in the small-amplitude
domain.

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It will be appreciated that the method of BSG synthesis
by Fourier techniques and the following quantization
presented here are not restricted to Delta-Sigma
quantization.

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Referring to Figure 32, there is shown a DSM feedback
process 320 that improves quantization after a loop
filter 322 by making use of the measured quantization
error 321. That is, DSM quantizes its input using a

20   threshold in unit 323, but keeps track of any important
information that is lost by the quantization in unit 323
and feeds this information back into its input in filter
322.   It will be appreciated that in alternate
embodiments any suitable digital quantizer can be used.

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Error Feedback and Iteration

Once the Fourier grating reflectance spectra has been
quantized, the synthesis is almost complete. The

30   grating's performance can be evaluated using a standard
test such as the transfer matrix method to determine
synthesis error. Synthesis error refers to the difference
between the desired reflectance spectrum and the spectrum

measured by the transfer matrix method. In one
embodiment, the error may be evaluated and used to offset
the design specifications by subtracting the error from
the grating's frequency-domain specifications. The new
5   specifications can then be used to repeat the synthesis
process and generate an improved grating. In an alternate
embodiment, the error, which is measured in the frequency
domain, can be appropriately transformed into the spatial
domain and added to the analog grating profile (the
10 grating before quantization). This latter form is a
general and powerful technique that can be utilized
independently of the synthesis method used in the
frequency domain. The error feedback process can be
repeated as desired, but a single iteration is often
15 sufficient. The convergence of the feedback process for
small-amplitude frequency regions is guaranteed by the
Fourier approximation described above.

It will be appreciated that the present invention
20 advantageously allows a designer to compare error
feedback correction with grating correction techniques in
order to correct for distortions in the diffraction-
characteristics domain. For example, certain peaks may
have characteristic shapes to which they distort in the
25 reflectance domain, for which either the above described
error feedback may correct. The present invention allows
the designer to weigh the advantages of error feedback as
compared with application of grating resources.

30   Alternate Embodiments of BSG Synthesis

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Induced-Symmetry Synthesis

Referring to Figure 33, an elementary property of sampled
signals is that their Fourier spectrum displays a
symmetry about integer multiples of a characteristic

5   frequency known as the Nyquist frequency. In certain
applications, such as filters with large numbers of
identical peaks, a similar symmetry exists in the
reflectance specification. The principle of Induced-
Symmetry Synthesis is that the symmetry of the

10 reflectance specifications can be reproduced by the
symmetry about the Nyquist frequency, such that the
grating's resources need only be used to create one half
of the spectral features.

15 A good example for this method is the synthesis of a
filter with ten equally spaced reflectance peaks. Using
the principle of Induced-Symmetry Synthesis, the designer
can choose a sampling length that places the Nyquist
frequency precisely in the middle of the ten peaks, that

20 is, on the line of symmetry of the specifications. The
designer can then proceed to synthesize a grating for the
five lower peaks. The upper five peaks appear
automatically due to the Frequency-domain symmetry.

25 Super-Nyquist Synthesis

Often the required resolution for grating inscription
exceeds the available resolution. For example, when
designing a BSG for the 1550 nm wavelength range in

30 Gallium-Arsenide ($n = 3.2$), it is convenient to place the
Nyquist rate at 1550 nm (to make use of Induced-Symmetry
Synthesis, for example), which corresponds to a sample
length of about 120 nm. This feature size is too small

for optical photolithography, and requires the use of the
more expensive electron-beam lithography.

However, Nyquist states that the frequency content above
5   the Nyquist limit consists of repeated copies, known as
images, of the spectral information below the Nyquist
limit. Thus, grating features above the Nyquist rate
(Super-Nyquist) may be generated by synthesizing their
grating image that are found below the Nyquist limit.
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In this manner, Super-Nyquist Synthesis is useful, for
example, for reducing the resolution required for the
1550 nm Gallium-Arsenide grating discussed above.
Choosing "third order" synthesis, the designer can select
15   the sample length such that the 1550 nm region
corresponds to three times the Nyquist frequency, as
indicated in Figure 34. The designer can then shift the
Fourier domain grating characteristics by integer
multiples of the sampling rate (twice the Nyquist
20   frequency), such that they are in the "baseband", below
the Nyquist frequency. A grating synthesized for these
shifted characteristics displays grating characteristics
where intended, just below three times the Nyquist
frequency, due to the phenomenon of imaging. Furthermore,
25   the sample length for this new grating is 360nm, which is
more appropriate for optical lithography. It will be
appreciated that applying Super-Nyquist Synthesis
advantageously reduces the resolution requirements.

30   Super Grating Applications
Supergrating scattering reduction

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Referring to Figure 1 there is shown a schematic of a
deep-grating BSG 14 formed in upper cladding 13 that
combines with core 12 and lower cladding 11 to form the
structure. A concern in supergrating design is scattering
5   losses due to radiative cladding modes, arising from low
spatial-frequency components in the grating. This
scattering arises from an incomplete enforcement of
phase-matching conditions in the direction normal to the
grating, and is more prevalent with shallow gratings.

10   Deeper etched features of the present invention reduce
this scattering by occupying a greater distance in the
normal direction, which from the well known Huygens
principle and Fourier considerations, leads to a more
robust phase-matching requirement in the normal
15   dimension; thereby reducing (unwanted) scattering
efficiency. More quantitatively, grating features should
ideally be deep-toothed to a depth exceeding the material
wavelength in the cladding ($\lambda_{mat} = \lambda_0/n_{clad}$), and the decay
constant of the modal tail should be less than $1/\lambda_{mat}$ in
20   the grating region (alternatively, the BSG can be
implemented in the core region 12 at the mode's center,
in which case the core 12 should be wider than λ_{mat}; or in
such a way that the index perturbation spans the entire
modal profile). This ensures relatively even
25   contributions from the normal extent of the grating,
thereby enhancing cancellation of the scattered
component.

The analysis follows by considering the product of the
index profile and modal profile 15: the wider and flatter
30   this product is, the narrower its Fourier transform, and
hence the narrower the k-space representation in the
normal direction. This increased restriction on the

23

phase-matching condition decreases the range (for example, in terms of output angle) over which a guided wave can couple to radiative modes, and hence reduces the aggregate scattering loss.

5   Referring also to Figure 2 there is shown a k-space illustration of the rationale behind baseband exclusion. Including the k-space baseband (i.e. low spatial frequencies) as an additional "region of interest" improves synthesis by drastically reducing the unwanted

10   higher-order coupling mediated by small-k components.

In alternate embodiments, supergratings may be implemented using any means of varying the effective (or modal) refractive index, including a surface relief embodiment (see Figure 31). One alternative is to effect

15   changes in modal index by varying the lateral dimension(s) of a one-dimensional waveguide. This can be accomplished in the case of a ridge waveguide 30 by varying its width, as shown in Figure 3 from a logic zero to a logic one value. This embodiment possesses many

20   advantages: the waveguide 30 and BSG 31 can be patterned and etched together, thereby simplifying fabrication; the waveguide and grating are automatically self-aligned, easing tolerances; and grating multi-level supergratings can be produced as easily as two-level BSGs.

25   2D (two-dimensional) supergratings

In one embodiment, the BSG takes the form of a one-dimensional sequence of high-index and low-index lines, and can emulate the near-arbitrary superposition of k-vectors (i.e. spatial frequency components) of differing

30   magnitude but like orientation. The BSG can be extended to two dimensions, where it takes the form of a matrix of

high- and low- index pixels implemented in the plane of a
planar waveguide; this can be further extended to include
any number of discrete levels. The 2D BSG (and the more
general 2D supergrating) can emulate the near-arbitrary

5   superposition of k-vectors of differing magnitude and
differing orientation (within the plane of the grating).
In practical terms, this means that the 2D BSG can route
and focus light according to wavelength and in-plane
input and output angles, thereby permitting

10   functionalities such as beam-shaping, wavelength-
selective lensing, and spatial multiplexing and
demultiplexing.

2D supergratings embodiments

Referring now to Figure 4 there is shown a schematic of a

15   prototypical 2D "supergrating" 40, referred to as a BSG,
standing for binary supergrating. A 2D supergrating is an
optical device having a 2-dimensional array of index-
modulated, effective-index-modulated, gain-modulated
and/or loss-modulated pixels nominally employing a finite

20   set of two or more levels of the modulated parameter or
parameters, and used in such a way that light propagates
in the plane of the array. The term "propagation layer"
will be used in referring to the layer through which the
light travels. The term "modulation layer" will be used

25   to refer to the layer carrying the physical change that
causes the change in the modal index of refraction of the
structure. In some cases, the two layers will be the
same — e.g. when ion implantation is used. In other
cases, they will be different as when a cladding layer is

30   etched or when a controllable finger is applied to make
contact with the propagation layer. Those skilled in the
art will readily be able to understand when the terms are

25

used.   The pixels can be arranged in any ordered or
periodic structure, e.g. a lattice arrangement, and can
employ any arbitrary but repeating shape. Shaded pixels
indicate a high index value and blank pixels indicate a

5   low index value.   Examples are arrays of rectangular
pixels on a rectangular array, point scatterers in a
triangular mesh, or hexagonal pixels in a hexagonal mesh.
The manufactured form of this device can exhibit non-
binary or even a continuum of modulation levels due to

10   the technical difficulties associated with producing a
perfect physical structure, but the pixels are
nonetheless inscribed with a finite set of inscription
methods or parameters corresponding to the ideal set of
levels that makes the device a 2D BSG. Such a device can

15   allow angle- and wavelength-specific optical processing,
in addition to emulating traditional optical components
such as mirrors and lenses.

The pixels of a 2D BSG are the quantized representation
of an analog profile that has been quantized by a method

20   that preserves Fourier information (neither adding or
subtracting features significantly) in one or more
regions of interest in the two-dimensional spatial
frequency representation of the grating, that correspond
to regions of interest in terms of angle- and wavelength-

25   specific diffraction characteristics.

Synthesis of 2D supergratings

One method of synthesizing two-dimensional supergratings
may be as follows:

30

A)   Determine a set of mathematical conditions that
describe the electromagnetic fields at the inputs and
outputs of the BSG in all modes of operations and
wavelengths.

5   B)   Compute an analog profile by solving a system of
equations corresponding, say, to the Born approximation
with boundary conditions corresponding to the input-
output conditions.

C)   Digitize the analog profile using a two-dimensional
10   technique designed to maintain Fourier components within
one or more regions of interest. One suitable method is
Floyd-Steinberg dithering, where the quantization error
made at each pixel is spread to the yet-to-be-quantized
pixels using a finite impulse response function
15   containing spectral information in the region(s) of
interest.

The process of grating synthesis may be illustrated with
20   reference to a simplified example. Figure 36A shows a
simple demultiplexer 36-10 for separating radiation
coming in from below on waveguide 36-2 and having two
wavelengths La and Lb into two outgoing paths 36-4 and
36-6, each having a single wavelength. Figure 36B shows a
25   simple demultiplexer using discrete components that
performs the same function. The example of Fig 36B uses a
prism 3 to separate the incoming wavelengths along two
paths 24' and 26' (both beams being bent in the same
direction). The separated radiation beams are bent back
30   into the correct path to enter the outgoing waveguides 4
and 6 by prisms 34 and 36. The beams are then focused
into the waveguides 4 and 6 by lenses 34' and 36'.

Figure 36A shows the same functions being carried out by an embodiment formed in a planar waveguide by solid-state techniques. An X-Y (directions indicated by axis 36-15)

5   array of pixels, denoted by lines along the left edge and bottom of box 36-10 form a BSG that perform the functions of separating the beams (in this case bending one wavelength to the left and the other to the right) at angles that vary with distance (angles A1 and A2 and B1

10   and B2) to provide separation. The angles are reversed in the region denoted by brackets 36-34 and 36-36, where the pixels perform the angular change and also focus the radiation. At the lower portion of box 36-10, the wavefronts are indicated by straight lines and at the

15   upper portion, denoted by curved lines representing the result of focusing into the outgoing waveguides 36-4 and 36-6.

It will be appreciated that the example of Fig 36A is

20   simplified in that the pixels in the upper portion only process a single wavelength, since the radiation has been separated in space. In many actual embodiments of a demultiplexer, the outgoing paths will be close or superimposed and the pixels will be processing more than

25   one wavelength. It is an advantageous feature of the invention that the synthesis of a refractive index profile to carry out the required functions is performed mathematically, rather than by illuminating a layer of material by a first interference pattern, then a second

30   pattern, etc., as in the past.

Referring to Figure 5, a 2D BSG can be used in
applications and devices that use 1D supergratings 50 or
other types of gratings in order to provide potential
5   advantages. These advantages stem from the fact that the
two-dimensional grating has well-defined coupling wave
vectors in both dimensions of the grating plane, and
hence offers direct control over coupling with radiative
modes and, therefore, the potential for reduced
10   scattering. The 1D grating 50, in contrast, often has
coupling wave vectors that are poorly defined in the
direction perpendicular to the waveguide, due to its
narrow width.

The "effective one-dimensional grating" corresponding to
15   a given two-dimensional grating can be thought of as the
1D index profile derived by integrating the 2D grating
along lateral lines perpendicular to the 1-dimensional
guiding. This effective 1D grating has index levels that
span a wide range of values between the two binary
20   levels, and with sufficiently high lateral sampling can
be almost analog in character (the number of levels will
be 2^1 for 1 binary lateral samples). As analog gratings do
not suffer from quantization problems, this can be used
as a method for a multi-level grating design that still
25   enjoys the robustness and eased fabrication benefits of a
binary-like physical structure.

The method can be summarized as including the following
steps:

- Compute an analog profile as with the prior method.

30   - Convert each pixel into a line of binary (or multi-
level) pixels, placed in the lateral direction

perpendicular to the 1D grating axis in such a way that
the average taken along that line closely fits the
desired analog value. This set of pixels is preferably
constrained to maintain certain symmetry properties in

5   order to reduce coupling to higher modes (with the
tradeoff of limiting the number of available lateral
averages). This line can be computed using a DSM-like
process (fed with the desired averaged value or with a
desired lateral profile); with a random-search

10   optimization method (for small numbers of pixels); or
by other methods.

The 2D supergrating can be implemented in a 1-dimensional
configuration by first sufficiently widening the 1D
waveguide to contain the 2D supergrating. The waveguide

15   can extend beyond the area and there contract to a
smaller (possibly single-mode) size. Additionally, two
waveguides can expand into such a 2D grating area (and
similarly contract on the other side) to create waveguide
couplers. 2D supergratings also offer reduced scattering

20   when implemented in conjunction with supergrating
waveguide couplers.

3D (three-dimensional) supergratings

The BSG can be further extended to three dimensions,
where it takes the form of a three-dimensional array of

25   high- and low- index pixels. As before, this definition
can be expanded to include any number of discrete levels.
The 3D BSG (and the more general 3D supergrating) can
emulate the near-arbitrary superposition of k-vectors
(i.e. spatial frequency components) of any magnitude and

30   orientation within one or more regions of interest
defined in 3D spatial-frequency space. In practical

30

terms, this means that the 3D BSG can route and focus light according to wavelength, input angles (i.e. polar and azimuthal), and output angles, thereby permitting functionalities such as those described for two-

5   dimensional gratings, but in the three dimensions of wavelength, polar angle, and azimuthal angle.

Referring to Figure 6 there is shown a schematic of a prototypical 3D supergrating 60 in an optical device including a 3-dimensional array of index, effective-

10   index-, gain- and/or loss-modulated pixels; nominally employing a finite set of two or more levels of the modulated parameter or parameters. The pixels can be arranged in any ordered or periodic structure and can employ an arbitrary but repeating shape. The manufactured

15   form of this device can exhibit non-binary or even a continuum of modulation levels either by design or due to the technical difficulties associated with producing a perfect specimen, but the pixels are nonetheless inscribed using a finite set of inscription methods or

20   parameters that correspond to the ideal set of levels that makes the device a 3D BSG. Such a device can allow angularly and chromatically specific optical processing, in addition to emulating traditional optical components such as mirrors and lenses.

25

Synthesis of 3D supergratings

Methods for synthesizing 3D supergratings include approaches very similar to those described above for 2D supergratings, except that the equations describe 3-

30   dimensional spaces and the quantization method uses a 3-

31

dimensional impulse response function to distribute the quantization error.

A 2- or 3-dimensional supergrating can be designed to create a structure featuring a complete or incomplete

5   photonic band-gap (PBG). This can be done by designing a grating with any of the BSG design methods that possesses spectral features within or near the desired band-gap with sufficient strength and density to create the gap. Synthesis can involve the entire applicable area, or

10 apply on a smaller scale to create a pattern that can be tiled to cover a larger area. The design may also use higher-order synthesis methods to allow for reduced resolution requirements.

A complete photonic band-gap material is one that

15 exhibits a range of frequencies that cannot propagate through the medium, regardless of the propagation direction. The applications of such a medium are numerous and abound in the literature. Some examples are: optical filters and resonators, inhibitors or enhancers of

20 optical radiation, materials for (super-) prisms, environments for novel laser and detector structures, and substrates for optical guiding and wiring.

The BSG-based photonic band-gap offers key advantages over prior-art PBG materials, including: lower index-

25 contrast requirements, and relaxed resolution requirements (both leading to higher compatibility with optical devices and eased manufacturing).

Synthesis of supergratings by optimization

A general method of designing supergratings of the one-, two-, or three- dimensional variety is presented here in addition to the methods described above:

5   • Generate an analog profile with a procedure such as that of the first synthesis method (let the function be called P).

       • Generate a filter H that determines the wavelength range(s) of importance (in which spectral features are
10   conserved) and their weights. H essentially assigns a weight for each frequency, where a high weight leads to better preservation of spectral information than a low weight. The filter H can be written in the form of a matrix operator to allow for a matrix solution of the
15   following step, but may also employ impulse-response or pole-zero forms.

       • Solve the optimization problem:

$$\min_{X,V} C = \min_{X,V} \left[\sum |H(P-X)|^L + \sum_i V_i (X_i - n_{low})(X_i - n_{high}) \right]$$

20   where X is a vector containing the values of the BSG, V is a vector of Lagrange multipliers, and L determines the type of norm for the optimization (L=2 corresponds to least-squares optimization, for example). The Lagrange multipliers force the BSG values to one of
25   the allowed index values (n_{low} or n_{high}), leading to a binary form. The function can be modified to allow for multi-valued supergratings in accordance with the teachings of the present invention.

The optimization can be carried out using any optimization method, although Newton-type methods are particularly useful and are presently preferred because of the matrix nature of the equation.

5   The approach can be applied to the synthesis of 2D and 3D gratings by taking the analog profile generated by the corresponding synthesis method and performing a similar optimization procedure, with the matrix equation modified to properly account for the dimensionality. This can be

10   done by stacking the rows of the 2-dimensional grating into one row of the X variable, likewise with the P variable, and synthesizing a corresponding H matrix.

An H matrix can be generated as a Toeplitz matrix of a given impulse response function, or with other methods

15   including:

Let h_f be a vector representing the importance weight of the spatial frequency f. Then H is given by:

$$H = F^{-1} \mathrm{diag}(h_f) F \, ,$$

where the n-dimensional F is the Fourier matrix given by:

20   $F_{jk} = \frac{1}{\sqrt{n}} e^{2\pi i jk/n} \quad (i = \sqrt{-1})$.

Multiplication by the matrix F is equivalent to taking a Fourier transform of a vector, an operation which can be sped up by using the Fast Fourier Transform (FFT) method. This fact can be used with H filters of this sort to

25   speed up the calculation of the cost function and its derivative to order n log(n).

Another alternative is to perform the optimization in the Fourier domain by considering both the P and X variables as their Fourier representations (generated by

34

multiplying by F), while suitably converting the equality constraints:

$$\min_{X,V} \tilde{C} = \min_{X,V}\left[\left|h_f{}^T(\tilde{P}-\tilde{X})\right|^2 + \tilde{X}^T F\,\mathrm{diag}(V)F^{-1}\tilde{X} - V\right]$$

$$\tilde{P}=FP, \quad \tilde{X}=FX$$

This representation can have the advantage of allowing

5   for sparse representations for the $\tilde{P}$ and/or h_f vectors, which can help reduce the computation time.

Tuning mechanisms for supergratings

The spectral characteristics of a supergrating can be

10 shifted by any mechanism that produces a change in effective modal index. This can be accomplished if an electro-optic, electro-strictive, magneto-optic, electrochromic, and/or photosensitive medium is present as part of the device thereby allowing one or more of the

15 design parameters to be modified using electronic control. Alternatively, modification of one or more of the design parameters can be effected using a change of the temperature, application of mechanical stress, and/or illumination of either the whole device or a section

20 thereof.

Tuning mechanisms can include, but are not restricted to, the following: thermal, electro-optic, magneto-optic, opto-restrictive, mechanical strain (external, piezo, electrostatic, magnetostatic, accoustic), current

25 injection, optical illumination, liquid crystal, reconfigurable molecules, chemical interaction, and mechanical translation.

35

For some devices, the benefit corresponds to a shift or
change in strength of spectral characteristics; for
others, functionalities beyond this emerge. In any case,
it is implicit throughout this patent application, and in
5   all device descriptions that follow, that the
functionality of devices employing static supergratings
can be further enhanced by replacing these with tunable
supergratings.

Programmable supergratings

10   Referring to Figures 7a-7d, there are shown exemplary
embodiments of programmable supergratings. A programmable
supergrating is a device that includes, in part, an array
of electrically addressable electrodes together with a
suitable medium, whereby the electrodes are used to
15   establish a grating pattern in the medium. The grating
pattern can be programmable, dynamic, or fixed. The
grating pattern can nominally utilize a finite number of
modulated levels (e.g. two levels for a BSG, more for a
supergrating), or utilize a continuum of modulated
20   levels.

Another embodiment (Figure 7a) includes an array of MEMS
(micro- electro- mechanical system) 7a2 fingers placed
above one or more waveguides 7a3; where each finger
corresponds to a "bit" of the BSG, and can be
25   individually deflected downwards to touch the waveguide
7a2 surface. Alternately, the "off" state can correspond
to contact between finger and waveguide, with "on"
deflection upwards and away from the waveguide. In any
case, the state with waveguide contact will generally
30   yield a higher effective index, and that with no contact
will yield a lower index. The preferred embodiment has an

off-waveguide separation sufficiently large that slight errors in this value negligibly change the lower effective index value, thereby facilitating true binary operation.

5   Yet another embodiment, shown in Figure 7b includes a plurality of electrodes disposed over encapsulated liquid crystals 7b2 (LCs) that affect propagation. In the nematic phase, LCs exhibit a birefringence that can be tuned with voltage, thereby yielding a means of tuning

10 effective index. This voltage-dependence typically has some threshold voltage V_t (corresponding to full alignment of nematic LCs) above which little or no further index change occurs. A method employing control voltages of $V = 0$ and $V > V_t$ should therefore facilitate true binary

15 operation, even in the face of confounding effects such as field fringing.

Co- and counter- directional asymmetric-waveguide BSG couplers

We begin by describing two fundamental elements of many

20 of the more complex devices that follow: namely, co-directional and counter-directional asymmetric-waveguide BSG couplers. These elements (which can indeed be devices in themselves) couple light from one waveguide to another parallel waveguide, with a desired spectral response:

25 i.e. light at a given wavelength can be coupled fully, fractionally, or not at all, and with a desired phase.

The general embodiment, Figure 7c, includes two parallel asymmetric waveguides, which will have differing effective modal indices $(n_{eff})_1$ and $(n_{eff})_2$, and hence

30 different propagation vectors $k_1(\lambda_0) = 2\pi(n_{eff})_1/\lambda_0$ and $k_2(\lambda_0) = 2\pi(n_{eff})_2/\lambda_0$, where λ_0 is free-space wavelength.

The effective indices will in general be dependent on wavelength λ_0. Signals from electronics drivers 7c3 are applied to electrodes denoted by 7c2 that change the modal distribution to induce coupling.

5   Light will couple co-directionally from one waveguide to another neighboring waveguide if their respective modal profiles overlap; this is known as intrinsic coupling, and will generally occur for all input wavelengths. Intrinsic coupling is a parasitic effect in the context

10 of BSG-enhanced coupling, and the optimal design seeks to ensure that the latter dwarfs the former. This condition becomes easier to satisfy as waveguide asymmetry (i.e. the difference between $(n_{eff})_1$ and $(n_{eff})_2$) increases.

15 Co-directional asymmetric-waveguide BSG coupler

Referring to Figure 8, there is shown a schematic of co-directional asymmetric-waveguide BSG coupler 80. Co-directional coupling from one waveguide 81 to another neighboring waveguide 82 (i.e. with overlapping modal

20 profiles) will be enhanced at a particular wavelength λ_0 if the waveguides' effective indices are perturbed with spatial frequency $K_g(\lambda_0) = k_1(\lambda_0) - k_2(\lambda_0)$. This can be accomplished using any BSG embodiment, including possibilities such as, but not limited to, placing a BSG

25 83 between the two waveguides, as described above; or implementing BSGs laterally in one or both waveguide, also described above. Arbitrary spectral coupling characteristics are achieved by having the BSG 83 emulate the appropriate spectrum of $K_g(\lambda_0)$.

30

Counter-directional asymmetric-waveguide BSG coupler

Referring to Figure 9 there is shown a schematic of counter-directional asymmetric-waveguide BSG coupler 90 coupling waveguides 91 and 92. For the above embodiment,

5   counter-directional coupling will occur for a given input wavelength λ_0 if the index perturbation instead includes a spatial frequency of $K_g(\lambda_0) = k_1(\lambda_0) + k_2(\lambda_0)$. The BSG 93 should be kept free of spatial frequencies of $2k_1(\lambda_0)$ and $2k_2(\lambda_0)$ over the entire spectral band of interest, as

10 these will produce back-reflection within the respective waveguides, thereby decreasing coupling efficiency and yielding undesired back-reflection. Satisfying this condition requires that waveguide asymmetry be sufficient to avoid any overlaps between grating spatial frequencies

15 (K_g's) yielding inter-waveguide coupling and those yielding intra-waveguide coupling, over all wavelength range(s) of interest; mathematically, this can be expressed as:

$$k_1(\lambda_1) + k_2(\lambda_1) \neq 2k_1(\lambda_2) \quad \text{and} \quad k_1(\lambda_1) + k_2(\lambda_1) \neq 2k_2(\lambda_2)$$

20 where k_1 and k_2 are defined earlier with wavelength-dependent effective index, and λ_1 and λ_2 are any combination of wavelengths lying within the range(s) of interest.

It will be appreciated that if either of the waveguides

25 is multimode, other overlaps should also be avoided, namely between the range of grating frequencies pertaining to desired and undesired coupling (whether co- or counter-directional).

Counter-Directional Symmetric-Waveguide BSG Coupler

Referring to Figure 10 there is shown a schematic of counter-directional symmetric-waveguide BSG coupler. The symmetric BSG counter-directional coupler performs the
5   same functions as the asymmetric counter-directional coupler (programmable, dynamic or static) but allows the two waveguides to be weakly asymmetric or even symmetric in their effective index. Thus, the limits expressed in the previous expression can be exceeded, albeit that this
10   would normally lead to intra-waveguide reflection. The method outlined below allows for efficient coupling between neighboring symmetric waveguides, while suppressing intra-waveguide reflection.

The device includes two waveguides (symmetric or
15   otherwise) with a BSG 612 placed between them. The BSG can be static, tunable, or programmable as necessary. Two more BSGs 611 and 622, identical to the middle BSG but with opposite contrast (1's become 0's and vice-versa), are placed on either side of the two waveguides such that
20   they mirror the center BSG about the corresponding waveguide.

The principle of operation is as follows: let m_1 be the modal profile of guide 1 and m_2 be the modal profile of guide 2. With loose notation, the coupling coefficients
25   relating the two waveguides can be written to first order in grating strength as:

$$C_{12} \propto \int m_1^* m_2 G_{12} + \int m_1^* m_2 (G_{11} + G_{22}) \cong \int m_1^* m_2 G_{12} \, ,$$

where G_{12} is the center grating and G_{11} & G_{22} are the gratings on the far side of waveguides 1 and 2
30   respectively. The second term is negligible because the

40

two side gratings are very far from the opposite
waveguide (more precisely, the opposite waveguide's modal
profile is negligible in this region).

However, the coupling coefficient from the first
5   waveguide to itself (corresponding to intra-waveguide
reflection) follows:

$$C_{11} \propto \int |m_1|^2 G_{11} + \int |m_1|^2 G_{12} = 0 \quad \text{(because } G_{11} = -G_{22} \text{ and symmetry)}$$

The result is identical for the second waveguide. The
only assumption necessary for the cancellation is that
10   the modal profiles of both waveguides be substantively
symmetric (about their waveguide, not necessarily
identical to each other; it will be appreciated that
waveguide coupling will generally introduce at least some
element of asymmetry) and that the gratings be properly
15   symmetrized about the guide. The cancellation is
independent of many material parameters such as the
waveguides' effective indices, even if they vary
independently.

BSG Couplers Using Lateral Waveguide Variations

20   This particular embodiment of implementing a BSG is given
special mention here due to its particular advantages, as
well as some anticipated further subtleties which will be
discussed later, such as: optimal width variation for
asymmetric-waveguide coupling, with particular regard to
25   the relative BSG strength in each waveguide; and how to
design the reverse-contrast grating of the symmetric-
waveguide coupler so as to minimize intra-waveguide
reflection.

The advantages of this embodiment are similar to those
30   described above, distinguished by the fact that there are

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now two (or more) waveguides, where the waveguide
alignment is critical. It will be appreciated, that the
waveguides and BSGs can be advantageously patterned and
etched together, thereby simplifying fabrication;
5   further, the waveguides and grating are automatically
self-aligned, easing tolerances.

BSG Crossbar switch

Referring to Figure 11, there is shown a schematic of a
grid-topology cross bar switch. The crossbar switch is a
10 device that routes wavelength channels from a number of
input waveguides to a number of output channels (usually
matching the number of input waveguides). The crossbar
switch generally needs to be able to route any wavelength
from any input waveguide to any output waveguide. These
15 switches are typically denoted by a N x N notation, where
N represents the product of the number of input/output
waveguides and the number of wavelength channels; for
example, a switch with 4 input waveguides, 4 output
waveguides, and 16 wavelength channels per waveguide is
20 called a 64 x 64 switch.

Traditional crossbar switches use a grid topology where
each of the n input waveguides is first de-multiplexed
into its c wavelength channels, resulting in nxc input
"rows" that are crossed over with nxc output "columns".
25 These columns are then multiplexed into groups fed into
the n output waveguides. Routing occurs by means of an
optical switch placed at each intersection of row and
column. This design is especially common with micro-
electro- mechanical systems (MEMS), where the switches
30 are implemented using movable mirrors. Clearly, this
topology requires $(nxc)^2$ switching elements.

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Another topology can use 2x2 switches, that is, switching
elements with two inputs (I_1 and I_2) and two outputs (O_1
and O_2); that either connects I_1 to O_1 and I_2 to O_2, or I_1
to O_2 and I_2 to O_1. The problem lies in choosing the

5 arrangement and number of switches so that the input
optical signals can be rearranged to all possible
permutations at the output. To determine the number of
switches required we can note that there are (nxc)!
possible permutations of the inputs; since every 2x2

10 switch provides one bit of control we can say that:

$$O\left(\log_2(nc)!\right) = O\left((nc)\log_2(nc)\right)$$

It will be appreciated that a programmable BSG (e.g., a
tunable co-directional or counter-directional coupler as
described above) can be used to form the 2x2 switch.

15 Thus, each BSG switching element can provide the 2x2
functionality independently for each input wavelength.
Advantageously, this eliminates the need to first
demultiplex the input waveguides, and reduces the number
of required switches:

20 $$\text{no. of switching elements} = O\left(n\log_2 n\right)$$

where n is the number of input waveguides only, leaving
no dependence on the number of wavelength channels c.
(See Figure 12, showing a schematic of one embodiment for
a 4-fiber switch, utilizing 6 switching elements 120.

25 Another embodiment can use layered 2x2 BSG switching
elements, where each layer has the same number of
switching elements equaling n/2, where n represents the
number of input waveguides, each carrying c wavelength
channels. In this embodiment, the switches can be

30 connected with each other in the following way:

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- Let waveguide w connect to waveguide w + 2^{1-1}, where 1 is the layer number (starting from 1).

- When $2^1 = n$ use the above formula by setting 1 = 1 again (wrap back).

5   This is only one particular wiring method and many more can be conceived, especially by drawing from prior art in binary switching tree design.

The number of switching elements employed by a design of this sort is given by:

10   $$\text{no. of switching elements} = \frac{n}{2}\,\text{ceil}\left[\frac{\text{ceil}[\log_2(n!)]}{n/2}\right],$$

where the ceil function generates the smallest integer number that is greater than its argument.

It will be appreciated that the savings generated by this design method can be enormous and are illustrated in
15   table 1.

Table 1

Input waveguides (n)	wavelength channels per input (c)	switching elements		
		grid design	single-wavelength layered design	multi-wavelength layered design
4	16	256	96	6
6	32	1152	384	12
8	64	4096	1024	16

While the number of switching elements in the
20   supergrating case are given by the formula above, the

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number of switches in the grid design case are specified
by $c \cdot n^2$, while the number of single-wavelength switches in
the layered design is given by c times the number of
switching elements in the BSG design.

5   In addition, embodiments using Programmable BSGs avoid
the need for multiplexers and demultiplexers, further
enhancing the savings. The single-wavelength design can
also be implemented with co-directional and counter-
directional couplers employing Bragg gratings instead of
10   BSGs.

Direct writing of BSGs in optical fiber

The following sections describe methods of implementing
BSGs in an optical fiber whose index and/or effective
modal index can be altered via exposure to intense and/or
15   high-energy laser light.

One-photon process

Referring to Figure 13 there is shown a One-photon method
of implementing a BSG in optical fiber. In this
embodiment, a grating employing binary or multi-level
20   features (index or effective index change, ablation, loss
modulation, etc.) is impressed upon a photo sensitive
optical fiber 13-1 by means of a switchable, focused
laser beam 13-10, that directly imprints the grating
information on the fiber as it is moved with respect to
25   the laser's focus as indicated by the arrow, at either
constant or variable speed. In an alternate embodiment,
the fiber is stationary and the laser's focus is
manipulated to scan the fiber.

Multi-photon process

Referring to Figure 14 there is shown a Multi-photon
device (two-photon shown here) 140 implementing a BSG in
optical fiber. A method similar to the above, with the

5   exception that two or more laser beams 144,145 are
employed for the process, and the information (i.e. shift
in index) is preferentially imprinted where a subset of
these beams intersect 143 and/or constructively
interfere. It will be appreciated that this embodiment

10   offers advantages whether the underlying photosensitivity
mechanism be intensity-dependent or energy-dependent. In
the former case, the constructive interference of N
(equal amplitude) beams yields N^2 times the intensity of a
single beam; in the latter, the setup can be arranged so

15   that aggregate photonic energy sufficient to effect the
transition in questions exists only where the beams
intersect.

This embodiment allows for increased control over the
region within the fiber upon which the information is

20   impressed (for example, index can be altered only at the
core 141 if the beams are made to intersect here), and
can also simplify manufacturing in that the outer
cladding need not necessarily be stripped, as can be
required for the single-photon process.

25   The following describes alternate embodiments of the
present invention that employ some combination of
supergratings and the modular elements of the previous
section. It will be appreciated that any BSG mentioned
here can be replaced by the more general multi-level

30   supergrating embodiment, which can in turn be replaced by
tunable and/or programmable embodiments in accordance
with the teachings of the present invention.

46.

Wavelength demultiplexer

A demultiplexer separates a multi-wavelength (i.e. multi-channel) input into its constituent channels. This demultiplexer functionality can be achieved using BSGs in
5   a variety of embodiments, described in more detail below.

Multi-level supergratings in accordance with the teachings of the present invention are also suitable for demultiplexers and filters with uneven channel spacing (or any other channel-spacing scheme). It will be
10   recognized that an advantage of such a demultiplexer embodiment of the present invention advantageously reduces problems such as SRS (stimulated Raman scattering), which are compounded when channels are equally spaced in terms of photonic frequency (energy).

15

Demultiplexer employing 1D supergratings

Referring to Figure 15 there is shown a schematic of a demultiplexer employing 1D BSG. This device includes, in part, a set of waveguides coupled using counter-
20   directional and/or co-directional BSG couplers 15-1 – 15-3, as described above, with the effect that multi-wavelength light entering the device through a specified input port is divided into its wavelength components, and which leave the device through their assigned output
25   ports.

Particular embodiments include: a cascade of co-directional and counter-directional BSGs, which successively divide the channels in two sub-bands until individual channels are extracted; and a sequence of
30   tilted single-channel gratings which direct individual channels to their respective output waveguide.

Demultiplexer employing 2D supergratings

This embodiment, shown in Figure 16, includes a 2D BSG
with the effect that multi-wavelength light entering the
5   device through a specified input port is divided into its
wavelength components, which leave the device through
their assigned output waveguides.

Add/drop filters

In this embodiment, an optical add/drop filter, as shown
10   in Figure 17, is an optical device 170 including an "in"
port 171, which accepts an input of multiple wavelength-
channels; a "drop" port 172, through which one or more
channels separated from the "in" stream are routed; and a
"through" port 174, from which the remaining channels
15   emerge. An additional "add" port may also be present,
which accepts inputs at wavelength-channels being dropped
from the "in" stream, and routes them to the "through"
output.

20   Static add/drop filter

Referring to Figure 18, there is shown an optical device
embodiment of the present invention, including one or
more 2D BSGs and/or a set of waveguides coupled using
counter-directional, and/or co-directional BSG couplers.
25   In this embodiment, one or more wavelength components of
light entering the device through a specified input
("in") port 181 is separated and leaves the device
through a specified output ("drop") port 184. The
remainder of the input light leaves the device through a
30   different output ("through") port 182. In addition, the

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device can include an additional input ("add") 183 port
with the property that particular, or all wavelength
components, entering the device through that port, also
leave through the "through" port 182 thereby being added
5   to the light routed there from the "in" port.

Still referring to Figure 18. BSG 1 couples a subset of
input λ's from waveguide A to waveguide B. BSG-2 couples
a subset of the first subset from B to C. This process
continues until only the desired wavelength(s) remain in
10   DROP waveguide. It will be appreciated that BSG-1 and
BSG-2 can be tuned to select desired λ over a range which
exceeds an intrinsic tuning range $\Delta\lambda/\lambda \approx \Delta n/n$. It will be
further appreciated that in alternate embodiments that a
counter directional coupling may be employed. In this
15   embodiment the Add port 183 can be made λ selective
through a similar Vernier approach.

Dynamic add/drop filter

Referring to Figure 19, there is shown an optical device
20   embodiment 190 including one or more 2D BSG and/or a set
of waveguides, where the waveguides are coupled using
tunable or fixed counter-directional and/or co-
directional BSG couplers with the same effective
functionality as the static BSG add/drop filter, but with
25   the addition that the wavelength(s) directed from the
"in" port to the "drop" port and/or the wavelength(s)
directed from the "add" port to the "through" port are
controllable by means of external control signals.

One particular embodiment makes use of the Vernier tuning
30   principle, with a design motivated by the fact that the
spectral shifts accessible through index tuning are often

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much less than the total desired tuning range. Multi-channel input enters along one waveguide, with light coupled to an adjacent waveguide by a multi-peak tunable BSG (with peak spacing generally less than the available

5   tuning range). A subsequent tunable BSG (generally multi-peak with a different spacing which also less than the available tuning range) couples a subset of this first set of channels to a third waveguide. This decimation process can continue as desired, with the BSGs

10   independently tuned relative to one another to drop desired channel(s). The channel selection range can thus greatly exceed the available index-tuned spectral shift. The same set of BSGs can be used to add the dropped channels from a second input, as shown in Figure 18.

15   Another embodiment uses a programmable BSG, enabling a structure such as that shown in Figure 19 that can dynamically add and drop any subset of input channels.

Wavelength stability monitor

To function properly, optical networks require that

20   channel wavelengths remain within some range of their nominal value. Drifting can be caused by a number of factors, including variations in environmental conditions, device aging, and mechanical disruptions.

Wavelength drift can be monitored using a 1D supergrating

25   in accordance with the teachings of the present invention, as shown in Figure 20a. While light incident at a given input angle on a tilted 1D 20a3 grating will nominally diffract at only a particular output angle, detuning from a central peak-reflectance wavelength will

30   in fact yield a detuning in angle, along with a decrease in diffraction efficiency.

This behavior may be used to detect shifts in wavelength,
or, assuming the wavelength to be true, shifts in device
characteristics which can then be compensated through a
variety of mechanisms (e.g. temperature tuning). In one
5   embodiment, a photodetector array 20a4 symmetrically
aligned along the diffraction path 20a2 of the desired
central wavelength may be used to detect wavelength
shift; in this configuration, the signal from each will
match if local wavelength matches the desired value.
10 (Note that diffraction efficiency will normally be
intentionally low, so that most power passes through un-
deviated.) Deviations in local wavelength are then
manifested by a change in the relative values of the
photodetectors 20a4, which can be monitored by passing
15 their outputs through a logarithmic subtraction processor
20a5 (other more sensitive functions may be employed).
These deviations can then be corrected for using
temperature or any other influencing parameter.

Similarly, an alternate embodiment can be implemented
20 with a 2D BSG 20b4 as shown in Figure 20b, which can
focus diffracted light to the detectors 20b3 and/or
detect drifts in wavelength on several channels
simultaneously; or with a sequence of quasi-1D (i.e.
point-source) features 20c3 etched along a waveguide 20c2
25 as shown in Figure 20c (detection and processing being
done in units 20c3 and 20c4), which will lead to
symmetric diffraction in both lateral directions. A
mirror may optionally be etched at one side, for optimal
collection of scattered light.

Tap-off network monitor

To dynamically re-configure channel assignments
("wavelength provisioning"), a network requires feedback
on channel usage; such reconfigurability is particularly

5   needed for metropolitan optical networks (MONs).

Network monitoring can be accomplished using 1-D or 2-D
supergratings in accordance with the teachings of the
present invention (Figure 21 shows a 2D network monitor
embodiment) to tap off a portion (typically small by

10   design) of input light and separate it into individual
channels. The separated channels are then focused on a
detector array 212, where their power is measured and the
information converted into a single electrical signal.
This signal can be processed by processor 214 and

15   transmitted to a monitoring station (not shown) in a
metro network along an electrical network, and provide
diagnostic data facilitating wavelength provisioning; or
aid in identifying problems in the network (e.g. showing
where a channel is losing power); compiling load

20   statistics; and measuring fault tolerance.

Multi-wavelength equalizer and gain-flattening filters

For optimal functioning, optical networks generally
require that wavelength channels be balanced in power.
Balancing typically occurs either within, or following

25   the amplification stage, and is correspondingly named
"gain-flattening" or "equalizing" respectively. A power-
balancing device can additionally serve to suppress
undesired signals such as the pump wavelength in optical
amplifiers.

Dynamic multi-wavelength equalizer

In this equalizer embodiment, dynamic equalization can be
achieved by routing input wavelengths through a tap-off
network monitor (Fig 22A) that separates channels and
5   monitors their respective power levels (see Figure 22B,
showing a curve of power versus wavelength). The signals
are then transmitted to an electronic processor, whose
output tunes (or programs) a sequence of BSGs in
accordance with teachings of the present invention, which
10   equalize the power across channels, e.g. by removing
power in various wavelength bands. Fig. 22C shows an
example of power removed as a function of wavelength.
Suitable, methods for clipping wavelength power include
using BSGs to couple input channels to an output
15   waveguide with lower efficiency or using BSGs to impose
higher scattering losses. Fig 22D shows the result of
subtracting appropriate amounts of power in a set of
wavelength bands, thereby producing substantially equal
power in each band.

20   One embodiment employs a cascade of BSGs that includes
"basis functions" which can be independently tuned to
effect the loss spectrum required for equalization;
suitable basis functions include step-like spectra that
can be shifted relative to one another.

25

Gain-flattened optical amplifiers

Figure 23 illustrates an alternate channel-balancing
embodiment. In this embodiment a BSG 23-1 (Fig 23A) is
incorporated directly within the amplifier that serves to
30   shape the gain spectrum as desired. The gain spectrum
(shown unperturbed in Fig 23B) can be flattened, or

tailored to any other profile, perhaps in anticipation of wavelength-dependent losses following amplification. Fig. 23C shows a loss coefficient spectrum matched to the gain spectrum of Fig 23B. Fig. 23D shows the combined gain

5   coefficient spectrum, combining the gain of the medium and the losses imposed on it. It will be appreciated that this embodiment offers much greater efficiency than typical post-amplifier equalization, which follows from recognizing that flattening the gain coefficient (the

10 gain per unit length within the amplifier) wastes far less power than flattening post-amplification gain.

Gain flattening, in accordance with the teachings of the present invention, can be applied to any optical amplifier, including Raman amplifiers, erbium-doped fiber

15 amplifiers (EDFAs), and semiconductor optical amplifiers (SOAs); as well as to multi-wavelength sources such as tunable lasers.

It will be appreciated that, gain flattening not only improves efficiency, but also can dramatically extend

20 amplifier bandwidth, particularly where the intrinsic gain spectrum is strongly peaked. This is especially true with semiconductor optical amplifiers (SOAs), whose bandwidth is so narrow as to provide gain for only a very few (often one) channels.

25 Lambda router

Lambda routers – also known as called wavelength routers, or optical cross-connects are devices positioned at network junction points which route wavelength(s) from a specific fiber optic input to another specific fiber

30 optic output. Lambda routers are generally NxN devices (i.e. with N input fibers and N output fibers), with each

input fiber typically conveying a single wavelength channel.

In a Lambda routing embodiment of the present invention, Lambda routing can be accomplished by coupling
5   demultiplexed input from a BSG-based device into an array of waveguides as shown in Figures 24a and 24b (i.e. one channel per waveguide). It will be appreciated that figures 24a-24b represent lambda routers when there is one input/output fiber and cross-bar switches when there
10 are multiple input and output fibers. A second array of waveguides exists beneath the first set, with each pair of top-waveguides and bottom-waveguides separated by a BSG with a flattop spectrum centered at the channel wavelength (i.e. co-directional or counter-directional
15 coupling). Cross/bar operation (i.e. channel light on one waveguide will couple to the other, and vice versa; or will remain on the same waveguide) is achieved by locally tuning the BSGs in or out of alignment with the channel wavelength. It will be appreciated that add/drop
20 functionality is a built-in aspect of this embodiment.

In Fig 24b, a grid topology router accepts multiplexed input on the left, having more than on incident wavelength on a channel in a lower
25 waveguide. At each intersection, a pass-band BSG couples wavelengths in a particular channel to the waveguides in an upper waveguide, running vertically in the drawing. The result is that $\lambda_{i,j}$ (wavelength lambda entering on the ith guide and having a
30 wavelength for the jth channel) is combined with the radiation of the same channel coming from other inputs.

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Figure 24A, having the same topology as shown in
Figure 12, is a more efficient arrangement for
achieving the same result.

5   Dispersion-slope compensator

Optical networks generally contend with a property known
as dispersion, especially where long transmission
distances and high bit-rates are involved. Dispersion
arises from the wavelength-dependence of effective index,
10   which in turn produces a wavelength-dependent group delay
spectrum for a given type and length of optical fiber.
The spectrum of an optical pulse is necessarily finite
(i.e. non-zero) in width; dispersion therefore spreads
out a pulse as it travels along a fiber, because its
15   various wavelength components will travel at slightly
different speeds.

Dispersion compensation can be achieved by "chirping" a
Bragg grating: modulating a grating's pitch along its
length z, as shown in Figure 25. Figure 25A shows an
20   embodiment in which the chirped grating is associated
with a circulator. Radiation is directed into the
grating, processed and returned to the circulator.
Figure 25B shows a transmissive fiber design. Figure 25C
shows a counter-directional BSG in which the grating the
25   couples two fibers also performs the chirping. Figure
25D shows a co-directional design. These designs produce
a wavelength-dependent phase spectrum which can be
tailored to provide the desired group delay spectrum:
$\tau_g = -d\phi/d\omega$. The delay for a given free-space wavelength
30   λ_0 then follows from the round-trip distance to where

local pitch has λ_0 as its Bragg wavelength:

$\tau_g(\lambda_0) = 2n_{eff}z(\lambda_0)$, where $z(\lambda_0)$ is the spatial coordinate at which $\Lambda(z) = \lambda_0/2n_{eff}$.

5   One dispersion embodiment of the present invention begins
    by determining the ideal (analog) input chirp function,
    as derived from the group delay spectrum $\tau_g(\lambda_0)$ (grating-
    imposed delay should of course be the opposite of that at
    the input). The ideal analog profile is then fed into a
10 quantization filter producing a binary profile that
    emulates the desired phase characteristics. The
    quantization filter can be further optimized for minimal
    phase noise.

    Alternate dispersion embodiments stem more directly from
15 the desired group delay spectrum.

    It will be appreciated that a variety of these types of
    embodiments are possible. One embodiment includes a 3-
    port circulator (light input at port i exits at port i +
    1, with port 3 "wrapping around" to port 1) that directs
20 light input to port 1 to a waveguide via port 2. A
    reflective BSG, in accordance with the teachings of the
    present invention, in the waveguide effects the desired
    compensating group delay spectrum, thereby directing the
    dispersion-compensated light back to port 2 of the
25 circulator, following which it emerges at output port 3.

    An alternate embodiment shown in Figures 26a and 26b that
    avoids the need for (and cost of) a circulator employs
    co- directional and/or counter-directional BSG couplers,
    which couple light from an input waveguide to subsequent
30 waveguide(s) so as to impose the desired group delay

                            57

spectrum. Depending on factors such as the compensation bandwidth, the temporal span of the group delay spectrum, and whether compensation is full-band or channelized, the intra-device propagation length can exceed the maximum

5   desired device size. In this case, dispersion compensation can be effected over successive waveguide couplings, with coupled waveguides arranged in a winding cascade.

It will be appreciated that embodiments of BSG-based

10   dispersion compensators offer many advantages such as emulating complicated chirp functions in a simpler fashion than present methods (present methods either tackle successive terms in a Taylor expansion of the dispersion characteristic, or achieve a "best-fit" to the

15   ideal delay spectrum using relatively few input parameters). Embodiments using BSG devices in accordance with teachings of the present invention can also provide dispersion compensation individually tailored to multiple simultaneous channels, offering an improvement over

20   solutions, which impose the same correction across all channels. Also, in contrast to some chirped-grating approaches, the embodiments using BSG devices in accordance with teachings of the present invention can be designed to yield a flat in-channel reflectance spectrum.

25

Tunable dispersion compensator

Tunable dispersion compensation can be achieved through an arrangement bearing some similarity to a combination of the cascade of co-directional and counter-directional

30   BSGs described above, and the earlier disclosed Vernier-tuning method, along with the dynamic multi-wavelength

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equalizer, also described above. Referring to Figure 26a, the cascade of BSGs includes group delay "basis functions" which can be independently tuned relative to one another to effect the desired group delay spectrum.

5   One embodiment, illustrated in Figure 26B, employs two tunable counter-directional BSG couplers, each implementing quadratic dispersion functions D_1 and D_2, with the functional forms:

$$D_1 = a_1(\lambda - \lambda_1)^2 + C_1 \quad \text{and} \quad D_2 = a_2(\lambda - \lambda_2)^2 + C_2,$$

10   where the center wavelengths λ_1 and λ_2 can be shifted independently through a tuning mechanism such as those outlined above. If the BSGs are cascaded and designed with $a_2 = -a_1$, the resulting dispersion is:

$$D_{net} = D_1 + D_2 = [2a_1(\lambda_2 - \lambda_1)] \lambda + [(\lambda_1^2 - \lambda_2^2) + (C_1 - C_2)],$$

15   which can be re-written in terms of $\Delta\lambda = \lambda_2 - \lambda_1$:

$$D_{net} = [2a_1(\Delta\lambda)] \lambda + [(2\lambda_1 + \Delta\lambda)(2\lambda_1 - \Delta\lambda) + (C_1 - C_2)]$$

Thus, dispersion slope $2a_1(\Delta\lambda)$ can be adjusted as desired by appropriately selecting $\Delta\lambda$, and the intercept is set by appropriately setting λ_1. This approach can be applied
20   to arbitrarily high orders of dispersion by employing next-higher-order dispersion basis functions.

Variable-feedback supergrating laser (tunable and/or multi-wavelength)

Referring to Figures 27a-27c, there is shown embodiments
25   of variable feedback supergrating lasers. In these embodiments, the programmable BSG is combined with an optical gain medium to produce a tunable laser with single-wavelength or multi-wavelength operation. In

Figure 27A, two programmable BSGs can create resonance at one or more wavelengths. In Figure 27B, a programmable BSG grating within the gain medium can control the output spectrum and also its power distribution. In Figure 27C,

5   the programmable BSGs can change the wavelength and also the angle, so that the wavelength and also the phase of the output radiation can be controlled.

It will be appreciated that any configuration employing

10   gratings as feedback elements, including but not limited to DBR, DFB, alpha-laser, and ring oscillator configurations, can be retrofitted by replacing some or all of the corresponding diffractive element(s) in the traditional design with programmable BSGs, in accordance

15   with the teaching of the present invention.

For a single-wavelength laser embodiment, the BSG-based device can control the position of the laser line, its line width, and/or its strength. In addition, it can be combined with monitoring of the above parameters

20   (directly or indirectly, such as through temperature, current, or voltage) to form a feedback system, to control one or more of these same parameters.

The BSG's design (or "program") can be altered in an otherwise similar configuration to produce a multi-

25   wavelength laser, offering independent control for each of several laser wavelengths or selection of a single wavelength. Lasing channels can be tuned, added, and dropped independently, and their relative output power can be balanced as desired. As described above, a monitor

30   can be added to form a feedback loop to control any of these parameters.

Beam combiner (reverse of beam-splitter)

A beam combiner as embodiment, as shown in Figure 28,
accepts input from one or more sources and streams them
5   into a common output. In Figure 28A, successive BSG
couplers add power at one or more wavelengths to the
power flowing from left to right in the horizontal
waveguide. In Figure 28B, a two-dimensional BSG accepts
three inputs and directs the radiation out along the
10   waveguide. Applications include combining the power from
multiple lasers (termed "power combiner" in this
context), as is done for example with Raman amplifiers to
achieve sufficient pump power. It would be especially
attractive in this case to integrate such a device
15   directly with the semiconductor laser array; the BSG is
very well suited for this purpose.

A variety of embodiments are possible, including some
combination of one or more BSG couplers and 2D
supergratings to combine multiple beams (possibly of the
20   same wavelength) into one. In the case of the 2D
supergrating, this essentially corresponds to the reverse
of splitting an input into multiple output beams.

Multi-wavelength/broadband isolator/circulator

Optical isolators are devices that block the passage of
25   one or more wavelengths along a waveguide, in one or both
directions. They are used to suppress back-reflection,
cross talk, and/or unwanted wavelength bands (e.g. pump
wavelengths).

A circulator is an N-port device which routes light input
30   at port i to port (i + 1), with input to port N "wrapped

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around" to port 1, and is often used in conjunction with
optical devices with an output emerging from the input
port (e.g. certain embodiments of optical delay lines,
dispersion compensators, and lambda routers).

5   Figures 29a and 29b-c show schematics of a BSG-based
isolator embodiment and 4-port coupled-waveguide
circulator, respectively. Both isolators and circulators
employ some means of subverting time-reversal symmetry:
i.e. light approaching the device from one direction is
10 treated differently from light approaching from the
opposite direction. This is typically achieved using
magneto-optic and/or optically active materials (such as
a Faraday rotator), in conjunction with birefringent
and/or polarizing elements.

15

Figure 29A, for example, shows an isolator in which
radiation coming in from the left passes through a
polarizer, then through a Faraday rotator that rotates
the polarization by 45 degrees, which passes through the
20 second polarizer. Radiation entering from the left is
polarized, rotated by the rotator and then blocked by the
second polarizer.

Figure 29B shows an example of a circulator, in which
25 radiation entering from the right on port 1 is rotated by
the rotator (e.g. 45 degrees), reflected back from port
3, rotated again and passes through the splitter to port
2.

Figure 29C shows an example of a rotator that may be used with the foregoing or other apparatus. Radiation enters from the left on the upper waveguide, is coupled to the lower waveguide by a BSG coupler in the presences of a
5   Faraday material and therefore also is rotated in polarization.

Supergratings, in accordance with the teachings of the present invention can be combined with magneto-optic
10   materials and/or polarizing elements to produce isolators and circulators offering wavelength-selective operation on pre-selected channels, or over broad band(s) of wavelengths.

15   BSG Photonic Band Gap materials

An important advance in optical theory in the past few decades is the concept of the photonic band gap (PBG). This realization that a two- or three-dimensional
20   periodic modulation of a material's refractive index can create optical wavelength ranges at which no light can propagate, regardless of direction, has proved to be fruitful in application. Applications include micro-dot lasers, sharp waveguide turns, high-Q optical filters,
25   and wavelength-selective optical couplers.

Nevertheless, the PBG is essentially a two- or three-dimensional extension of the Bragg grating. The BSG concept, as an extension of the Bragg grating into
30   wavelength space, may be combined with the PBG to create a whole new set of optical materials.

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A highly advantageous feature of BSG-PBG materials may
        well be their departure from the high refractive
        index contrasts required by conventional PBG
        materials.   Embodied as a periodic lattice of
5   refractive index features, conventional PBGs exhibit
        different periodicity in different directions. Each
        direction is therefore characterized by a different
        effective Bragg grating, each in turn associated
        with a particular band gap - a range of wavelengths
10   prohibited from propagating in that direction as a
        consequence of the grating. The width of this
        wavelength gap is directly proportional to the
        effective grating's strength, which in turn
        corresponds to the PBG's refractive index contrast.
15   However, to forbid propagation for a particular
        wavelength for all directions, thereby forming the
        "complete" bandgap which defines the PBG, all the
        individual wavelength gaps must overlap at the
        wavelength in question, thus, as those skilled in
20   the art are aware, imposing a minimum refractive
        index contrast for the PBG.

    Fig. 37 shows in Figure 37A a hexagonal arrangement of
        dots representing regions of different refractive
25   index.   Figure 37B shows a corresponding hexagon in
        wave number space.   Those skilled in the art are
        aware that ordinary materials exhibiting the PBG
        effect have a regular geometric arrangement that
        produces an outline in wave number space.   In Figure
30   37B, for example, the hexagonal array of dots in
        Figure 37A is reflected in a hexagon in k-space.   In
        order to suppress radiation propagation (of a
        certain wavelength represented by the dotted circle)

in all directions, therefore, the thickness of the
hexagon in k-space must be such that the circle
representing the relevant wavelength can be
inscribed within the band-gap hexagon. This
5   requirement imposes a requirement of unneeded band
gap suppression. For example, the regions at the
outer corners of the hexagon in Figure 37B is not
needed, since the dotted line is at the inner
corners. Similarly, the regions in the centers of
10   sides are not needed because the dotted line is at
the outer edge in that area.

Unlike conventional PBGs, the BSG is not restricted to a
periodic lattice and its implied directional variation in
15 periodicity. Instead, a two- or three-dimensional BSG can
be designed to exhibit a near-arbitrary band of effective
periodicity in any direction. This corresponds directly
to the one-dimensional BSG's control over its diffractive
spectrum This design freedom obviates the reliance on the
20 grating's refractive index contrast to thicken the
individual band gaps until they overlap. Instead, the
pattern of index change may be set geometrically to
reinforce the refractive index patterns of the band gaps
that cause overlap in the first place. Any extra
25 strength afforded by the available index contrast can
then be applied to subject more wavelengths to the PBG's
effect. Figure 38 shows in Figure 38A a non-periodic
arrangement of pixels that provide for the suppression of
transmission in a particular wavelength range in any
30 direction in a more economical use of resources. The
angular dependence of the pixel pattern is set such that
the dotted line (the same dotted line as in Figure 37) is
bounded by a smaller, uniform margin. If desired, the

margin in Figure 38 could be increased to cover a greater
wavelength range.

Thus, for a given technique of index modulation (e.g. ion
5   implantation) a BSG-PBG material can exclude a greater
wavelength range than conventional PBG materials.

In addition, the new materials according to the invention
may, in the same area, exclude radiation in a first
10   wavelength range and manipulate radiation in one or more
other wavelength ranges - e.g. exclude pump radiation
while deflecting, focusing, etc. radiation in a generated
wavelength band.

15   The dramatic reduction in the necessary refractive index
contrast offered by the BSG-PBGs synthesis may indeed
overcome a major practical challenge in PBG fabrication.
However, this reduction comes at a cost: a lower-contrast
grating also implies a longer required interaction length
20   through which the grating affects light. This is also
true for the PBG, however, and while the effect may be an
important consideration for certain applications, it may
be mitigated, overcome or even prove beneficial for many
others.

The BSG can do more than simply improve upon the
practicality of PBG implementation. For example, the BSG
enables materials exhibiting several photonic band gaps,
stemming directly from the capacity to emulate several
5   superimposed gratings which inspired our first
explorations. Such materials may be useful in a number of
applications, primarily those employing several optical
wavelengths, such as systems with separate pump and
signal wavelengths, as well as wavelength converters.
10   More generally, the BSG allows for complete control over
the optical band structure, including the width and
position of band gaps as well as the optical density of
states and the dispersion relation.

15   Figure 39 shows a cross section of a high efficiency
solar cell or other photodetector using a PBG material
according to the invention. Substrate 39-10 is a
conventional material that exhibits the photoelectric
effect, e.g. silicon. Layer 39-20 is a material that
20   ordinarily permits the propagation of light of the
relevant wavelength. According to the invention, a BSG-
PBG pattern has been impressed on the material 39-20, so
that propagation in the transverse direction indicated by
arrow 39-17 is suppressed. Radiation that would
25   otherwise propagate transversely is then scattered by the
BSG-PBG pattern and winds up preferentially scattering
with a vertical component (e.g. according to arrow 39-
15). A greater fraction of the incident radiation is
thus absorbed by the photoelectric material 39-10.

30

Figure 40 shows an array of PBG material 40-1 arranged in
a customary pattern. Two dots of the pattern, 40-2, have
been removed, establishing a pair of micro-dot lasers

(conventional pump radiation being omitted for clarity).
As many microdot lasers as desired may be arranged in any
desired geometrical layout.

5   Figure 41 shows a top view of a BSG-PBG material 41-5
     that excludes radiation in a relevant wavelength range.
     The BSg pattern does not extend to waveguide 41-10, which
     therefore permits the passage of radiation in that
     wavelength range. A curve having a radius of curvature
10   R, less than the conventional limit, referred to as a
     reference value, has been formed in the waveguide. Those
     skilled in the art are aware that a conventional material
     would have an excessive amount of scattering when passing
     through a curve with a radius of curvature less than the
15   reference value. The BSG-PBG material permits the
     formation of the waveguide with reduced losses.

     Figure 42 illustrates a pair of waveguides 42-10 and 42-
     12 formed in a BSG-PBG material 42-5. As an optional
20   feature, the area 42-25 between the two waveguides has
     been provided with a BSG-PBG material 42-25 that has a
     longer attenuation length at the wavelength being
     transmitted by waveguides 42-10 and 42-12. Thus,
     coupling between the waveguides is facilitated. The
25   different material is not necessary, and the same
     material could be used, with an appropriate spacing
     between waveguides (or the BSG-PBG material could be
     omitted between the waveguides).

30   As an additional option, the general provision of PBG
     could be dispensed with and a PBG could be placed between

the waveguides 42-10 and 42-12. The material between the two waveguides could be fabricated to permit coupling between the waveguides, e.g. by structuring the PBG pattern such that propagation parallel to the waveguides

5 is not allowed, but propagation (i.e. coupling) between the waveguides is allowed.

The foregoing is an example of a directional PBG material

10 meaning a material having a pixel pattern that suppresses propagation within a wavelength band in selected directions.

Figure 43 illustrates a top view of a unit employing a

15 non-linear effect. Rectangle 43-05 represents an area of a material that exhibits a non-linear effect and also has been impressed with a PBG pattern that suppresses propagation at wavelengths λ_1, λ_2 and λ_3. In the example illustrated, λ_1 and λ_2 are pump wavelengths, propagating

20 along waveguides 43-10 and 43-15, respectively and λ_3 is the output wavelength of the relevant non-linear interaction, propagating along output waveguide 43-20. The initial section of waveguide 43-20 is an optional waveguide in this device that may be used, e.g. to supply

25 input radiation at λ_3, to which the result of the non-linear interaction will be added.

Radiation at λ_1 and λ_2 combine in the overlap area to generate radiation at λ_3, as is known in the art. The PBG

30 pattern outside the waveguides confines the radiation.

Within section 43-12 of waveguide 43-20, a pixel pattern
43-26 focuses the output radiation to a point as shown.
Section 43-25 of the waveguide 43-20 reflects radiation
at the output wavelength, so that it is directed as

5   required (upward in the drawing) and is not wasted. If
desired, or if required by limited resources, the PBG
pattern on the left, denoted by 43-07, could be set to
confine radiation of λ_1 and the pattern on the right,
denoted by 43-06, could be set to confine radiation of λ_2,

10 with the radiation λ_3 being confined only by the pattern
in the area 43-12. Thus, the (limited) capabilities of
the PBG pattern could be reserved for use only where
required.

15 It should be understood that the foregoing description is
only illustrative of the invention. Various alternatives
and modifications can be devised by those skilled in the
art without departing from the invention. Accordingly,
the present invention is intended to embrace all such

20 alternatives, modifications and variances, which fall
within the scope of the appended claims.